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GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA

COMPUTER EVALUATION OF RAWINSONDE DATA FOR SPACE VEHICLE APPLICATIONS

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By

Halsey B. Chenoweth
and
Bettye Anne Busbee

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ABSTRACT

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Procedures for computing certain thermodynamic and kinematic properties of the atmosphere from radiosonde observations have been developed and are outlined in a variety of sources. The purpose of this report is to: (1) Select certain of these procedures, (2) discuss the theory involved in method choices of handling raw data, (3) compute the necessary functions for smoothing and presenting the data, and (4) present a program for machine computation of the atmospheric parameters.

The body of the report deals with evaluation of atmospheric parameters through the altitude range for which radiosonde-measured values are available and reliable. The procedure for extrapolating parameter values at higher (30 km) altitudes is presented as an appendix. The technique outlined for rawinsonde data evaluation was developed to provide a scheme for direct interjection into MSFC flight evaluation programs.

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TERRESTRIAL ENVIRONMENT SECTION
AEROPHYSICS AND ASTROPHYSICS BRANCH
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DEFINITION OF SYMBOLS

a = Recorder division parameter (exponent in basic relative humidity term)

A = Exponent (temperature recorder division transformation term)

C = Recorder division parameter (denominator in basic relative humidity term)

D_f = Recorder division value (humidity)

D_t = Temperature recorder division value

e_a = Actual vapor pressure (mb)

e_s = Saturation vapor pressure (mb)

f_{cal} = Recorder calibration point

f_{-40} = Calculated recorder division point

g = Acceleration of gravity (m/sec^2) $g = 9.80665 \frac{m}{sec^2}$

$L_M = \frac{dT}{d\phi_d}$ = Lapse rate of temperature with geopotential height ($^\circ$K/m')

m' = Geometric meters

n = Index of refraction of light through earth's atmosphere

N = Number of observations or number

p = Ambient pressure (mb)

P = Ambient pressure (kpm^{-2})

P_b = Base pressure in the appropriate units

Q = Function of recorder calibration point (basic relative humidity term)

r_a = Relative humidity (%)

r_g^* = Parameter used to convert geopotential function to geometric meters (m)

r_o = Mean radius of earth throughout radiosonde measurement area (m)

r_{s1} = Slant range from radar site at angle θ (m)

DEFINITION OF SYMBOLS (Cont'd)

r' = Parameter used to convert geopotential function to geometric meters (m')

R = Gas constant for dry air = 2.8704×10^6 erg/gm ($^\circ$K)

S = Wind shear (sec^{-1})

t = Time (sec)

T = Ambient temperature ($^\circ$K), $T = t' + 273.15$

t_{cal} = Recorder calibration point

T_{MOL} = Molecular temperature ($^\circ$K)

T_{MOL_B} = Base molecular temperature ($^\circ$K)

t' = Ambient temperature ($^\circ$C)

T^* = Virtual temperature ($^\circ$K)

T^*_m = Mean virtual temperature of a layer ($^\circ$K)

U = Zonal component (m/sec)

V = Meridional component (m/sec)

W = Wind velocity (m/sec)

W_x = Wind velocity component to firing direction (m/sec)

W_z = Wind velocity component parallel to firing direction (m/sec)

X = Zonal position coordinate (m)

Y = Geometric height (m)

Z = Meridional position coordinate (m)

α = Missile firing angle from true north (degrees)

β = Constant (ARDC Model atmosphere pressure equation)

Δh = 250 m

θ = Elevation angle from plane tangent to earth (degrees)

ξ = Wind angle with respect to true north (degrees)

6

DEFINITION OF SYMBOLS (Cont'd)

ρ = Ambient density

ϕ = Geopotential height: Geopotential m^2/sec^2 (unit geopotential = 98×10^3 erg/gm)

ϕ_{dB} = Geopotential height at base of a constant temperature layer ($m' = m^2/sec^2$)

ψ = Azimuth angle from true north (degrees)

Subcripts

c = Cartesian coordinate system

cal = Calibrated

d = Derived

int = Interpolated

o = Sea level

s = Spherical coordinate system

u = Oriented in the x direction

v = Oriented in the z direction

w = Wind

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SUMMARY

This report presents the equations and techniques of deriving the necessary atmospheric parameters, utilized in space vehicle trajectory computations, obtained from radiosonde observational data. Techniques are derived for smoothing the radiosonde balloon position coordinates in spherical coordinates with respect to the origin (balloon launch point). Flight path referenced winds utilizing a spherical and a Cartesian model are also derived. The procedure for extrapolating the radiosonde data for higher altitudes is presented as an appendix.

SECTION I. INTRODUCTION

The procedures for computing thermodynamic and kinematic properties of the atmosphere from radiosonde* observations have been outlined in previous works. The purpose of this report is to organize these procedures from diverse sources into a form for computer use, including the latest techniques and information in the report where applicable.

The method of extrapolating the radiosonde observations, up to and including orbital altitudes, is outlined in the appendix. This extrapolation is necessary for determining the basic environmental parameters associated with space vehicle trajectory analysis.

The author wishes to acknowledge the valuable help of Mr. David Young, Digital Projects Branch, Computation Division, who made it possible for this report to be readily adaptable for machine computation procedures.

* In this report radiosonde is used with reference to the AN/GMD-1( ) system.

Grateful acknowledgement is due Miss Mildred Letherwood, Data Reduction Branch, Computation Division, for final programming and whose helpful suggestions in the data smoothing techniques have greatly enhanced the value of this report.

SECTION II. ANALYTICAL PROCEDURES

A. Basic Information. Radiosonde observations measure temperature (C), pressure (mb), and relative humidity (%). The radio direction finder tracks the radiosonde balloon, and measures the elevation angle (θ) from a tangent to the earth at the point of observation and the azimuth angle (ψ) from true north.

Azimuth and elevation angles, pressure, temperature, and humidity are determined at constant time intervals. For computation and analysis the latitude, date and time of release, and date and time of observation termination are necessary.

There are analytical techniques designed to compensate for small instrumental, computational, and observational inaccuracies. Space averaging is defined as the process of averaging two position points and attributing that average to a mid-point. Curve smoothing is defined as the process of eliminating small discontinuities and/or negative curvatures from observational data or computed functions which are assumed continuous in nature. Space averaging and curve smoothing sometimes overlap in their purposes of application, and are both used at appropriate places in the computations of this report.

B. Discussion of Thermodynamic Quantities. Temperature and relative humidity are given in recorder division values. These ordinates are transformed to actual values of temperature and relative humidity through calibration parameters. Computation of other necessary parameters from the transmitted data is accomplished through use of certain standard or recently published procedures (References 1, 4, 5, 6, 9, 10).

C. Discussion of Wind Quantities. Wind direction is measured clockwise from true north to the direction from which the wind is blowing. In regard to sign, wind will imply the following conventions:

a. When the wind is blowing from the south to true north, V and Z are positive.

b. When the wind is blowing from west to due east, U and X are positive.

A transformation of zonal and meridional wind components to the flight path coordinate system is made.

Data smoothing is designed to give continuity at all points to the variable or variables under consideration. Smoothing of the radiosonde position coordinates is considered necessary. The root-mean-square deviations from the smoothed values are compared with the standard deviations of the theoretical errors. The swinging of the balloon causes small random oscillations in the pressure, temperature, and humidity. Errors attributed to these latter quantities are considered to be small and will be neglected in this procedure.

The smoothing procedure used is actually a least squares method rather than a smoothing technique as generally considered. The procedure suggested as a means of reducing computing time and increasing efficiency is more fully described in Section III.

SECTION III. COMPUTATIONAL PROCEDURES

A. Basic Data. Raw data, on occasion, will have many diversified formats. The format of the essential data is given in Display I, including relative humidity ordinate, temperature ordinate, pressure, elevation angle, azimuth angle, and time.

DISPLAY I

r_a	t'	p	θ	ψ	t
ordinate	ordinate	mb	deg	deg	min

The information that must be recorded at the beginning of radiosonde observation includes: Station, station height, Greenwich meridian release time, wind magnitude and direction at ground level, and record division lock-in values for both temperature and humidity.

The program outlined herein allows the raw data to be put on IBM cards, paper tape, or magnetic tape, and then run into the computer in fixed point or floating point routines depending on programming needs.

B. Computation of Thermodynamic Quantities.* Conversion of Recorder Division Values to Actual Measurement: (Reference 1)

Step 1 - Compute basic relative humidity term:

$$f_{-40} = f_{cal} + \left(\left| \frac{46-D_f}{C} \right| \right)^a \cdot \left(Q \right)$$

when $46-D_f$ is positive:

* All quantities are computed for each time point t for which data is available.

$$C = 64.8 - \frac{f_{cal}}{2.51}$$

$$Q = 100 - f_{cal}$$

$$a = 1.66 + \left(\frac{46-D_f}{33}\right)$$

when $46-D_f$ is negative:

$$C = \frac{f_{cal}}{1.45} - 5.198$$

$$Q = 10 - f_{cal}$$

$$a = 0.5 + \left(\frac{46-D_f}{-10}\right)$$

Step 2 - Compute temperature:

$$t' = \left[\left|\frac{D_t - 37.6}{b}\right|\right]^A \left[\left(\frac{t'_{cal} + 20.525}{2.2625}\right) + 64\right] + t'_{cal}$$

if $D_t - 37.6$ is positive, then:

$$b = 39.4$$

$$A = 1.177 + \tfrac{1}{2}\left[\frac{D_t - 37.6}{b}\right]^2$$

if $D_t - 37.6$ is negative, then:

$$b = 34.6$$

$$A = 1.24 + 1.0638297872\left[\frac{D_t - 37.6}{b}\right]^2$$

NOTE: If $D_t - 37.6$ is negative, then $\left[\left|\frac{D_t - 37.6}{b}\right|\right]^A$ must be given a negative sign, and t'_{cal} always is a negative number.

Step 3 - Compute relative humidity:

$$r_a = f_{-40} + \left[\frac{D_f(f_{-40} - 33)}{1050}\sqrt{t' + 40}\right]$$

NOTE: When $\sqrt{t' + 40}$ equals to zero or an imaginary number (i.e., when $t' \leq -40°C$) the value of the factor is considered zero, then $f = f_{-40}$. Also, humidities less than 5% are considered zero, and humidities higher than 99% are printed as 99 percent.

Fundamental Standard and Empirical Equations (Ref. 1, 4, 5, 8, 9, 10):

Step 1 - Compute saturation vapor pressure:

$$e_s = 6.11 \times 10^{\left(\frac{7.5\,t'}{t' + 237.3}\right)} \text{ (mb)}$$

Step 2 - Compute actual vapor pressure:

$$e_a = r_a(\%)e_s \text{ (mb)}$$

NOTE: $r_a(\%)$ must be changed to a decimal fraction

Step 3 - Compute virtual temperature:

$$T^* = T\,\frac{(p + 0.00123\ e_a)}{(p - 0.37812\ e_a)}\ (^\circ K)$$

Where p and e_a are in millibars

Step 4 - Compute pressure in kp/m^2

$$P(kpm^{-2}) = 10.1971621\ p\ (mb)$$

Step 5 - Computation of density:

(a) $$\rho\ (kp\ sec^2 m^{-4}) = 0.0355252\ \frac{p\ (mb)}{T^*\ (^\circ K)}$$

(b) $$\rho\ (kpm^{-3}) = 0.0355252\ \frac{P(kpm^{-2})}{T^*\ (^\circ K)}$$

Computation of Pressure Height:

Step 1 - Compute mean virtual temperature:

$$T_{m_n}^* = \frac{T_{n+1}^* + T_n^*}{2}\ \text{(K) where } n = 1, 2, \cdots, N-1.$$

Step 2 - Compute for every time interval:

$$\Delta\phi_n = 29.2897959\ T_{m_n}\ \ln \frac{P_n}{P_{n+1}}\ (m')$$

Where n = 1, 2, ···, N-1

Step 3 - Compute geopotential function:

$$\phi_{d_n} = \phi \text{ station height} + 29.2897959 \sum_{i=1}^{n-1} T_{m_i}^*\ \ln \frac{P_i}{P_{i+1}}\ (m')$$

Step 4 - Compute geometric height, Y_s(m):

$$Y_s = \frac{r_g^* \phi d_n}{r' - \phi d_n} \quad \text{(m)}$$

NOTE: Some characteristic values of ϕ station height, r_g^* and r' are given in Table A for Atlantic Missile Range. These parameters are a function of latitude and are taken from the Smithsonian Meteorological Tables (ref. 5).

TABLE A

Characteristic Parameters of Geopotential Station Height, r_g^* and r'

	ϕ Station Height (m')	r_g^* (m)	r' (m')
Patrick Air Force Base	4	6,344,520	6,339,260
Cape Canaveral	5	6,344,790	6,339,760
Grand Bahama Island	7	6,343,550	6,337,530

C. Computation of Wind Quantities. Position Coordinate Smoothing:

$$\text{Define} \quad r_{sl} = \frac{r_o + Y_s}{\cos\theta} \cdot \cos\left\{\theta + \sin^{-1}\left(\frac{r_o\cos\theta}{r_o + Y_s}\right)\right\} \qquad (1)$$

$$X_s = r_{sl}\cos\theta\sin\psi\sin\left\{\theta + \sin^{-1}\left(\frac{r_o\cos\theta}{r_o + Y_s}\right)\right\} \qquad (2)$$

$$Z_s = r_{sl}\cos\theta\cos\psi\csc\left\{\theta + \sin^{-1}\left(\frac{r_o\cos\theta}{r_o + Y_s}\right)\right\} \qquad (3)$$

Assuming that p, T, r_a and Y_s are errorless, for smoothing of the error that azimuth and elevation angles (θ and ψ) cause in position coordinates, compute theoretical error:

$$\Delta r_{sl} = \frac{\partial r_{sl}}{\partial\theta}\Delta\theta$$

$$= \sec\theta\,\Delta\theta\,(r_o + Y_s)\left[\left[\left[\tan\theta\cos\left\{\theta + \sin^{-1}\left(\frac{r_o\cos\theta}{r_o + Y_s}\right)\right\}\right]\right.\right.$$

$$\left.\left. - \left[\sin\left\{\theta + \sin^{-1}\left(\frac{r_o\cos\theta}{r_o + Y_s}\right)\right\}\right]\right]\left[1 - \frac{r_o\sin\theta}{\sqrt{(r_o + Y_s)^2 - r^2\cos^2\theta}}\right]\right] \qquad (4)$$

$$\Delta X_s = \frac{\partial X_s}{\partial r_{sl}} \Delta r_{sl} + \frac{\partial X_s}{\partial \theta} \Delta\theta + \frac{\partial X_s}{\partial \psi} \Delta\psi$$

$$= \cos\theta \sin\psi \csc\left\{\theta + \sin^{-1}\left(\frac{r_o \cos\theta}{r_o + Y_s}\right)\right\} \Delta r_{sl}$$

$$- r_{sl} \sin\psi \csc\left\{\theta + \sin^{-1}\left(\frac{r_o \cos\theta}{r_o + Y_s}\right)\right\}$$

$$\cdot \quad \sin\theta + \cos\theta \left[\operatorname{ctn}\left\{\theta + \sin^{-1}\left(\frac{r_o \cos\theta}{r_o + Y_s}\right)\right\}\right]$$

$$\cdot \left[1 - \frac{r_o \sin\theta}{\sqrt{(r_o + Y_s)^2 - r_o^2 \cos^2\theta}}\right] \Delta\theta$$

$$+ r_{sl} \cos\psi \cos\theta \csc\left\{\theta + \sin^{-1}\left(\frac{r_o \cos\theta}{r_o + Y_s}\right)\right\} \Delta\psi \quad (5)$$

$$\Delta Z_s = \frac{\partial Z_s}{\partial r_{sl}} \Delta r_{sl} + \frac{\partial Z_s}{\partial \theta} \Delta\theta + \frac{\partial Z_s}{\partial \psi} \Delta\psi$$

$$= \cos\theta \cos\psi \csc\left\{\theta + \sin^{-1}\left(\frac{r_o \cos\theta}{r_o + Y_s}\right)\right\} \Delta r_{sl}$$

$$- r_{sl} \cos\psi \csc\left\{\theta + \sin^{-1}\left(\frac{r_o \cos\theta}{r_o + Y_s}\right)\right\}$$

$$\cdot \quad \sin\theta + \cos\theta \left[\operatorname{ctn}\left\{\theta + \sin^{-1}\left(\frac{r_o \cos\theta}{r_o + Y_s}\right)\right\}\right]$$

$$\cdot \left[1 - \frac{r_o \sin\theta}{\sqrt{(r_o + Y_s)^2 - r_o^2 \cos^2\theta}}\right] \Delta\theta$$

$$- r_{sl} \sin\psi \cos\theta \csc\left\{\theta + \sin^{-1}\left(\frac{r_o \cos\theta}{r_o + Y_s}\right)\right\} \Delta\psi \quad (6)$$

The theoretical error of the position coordinates is given in equations (5) and (6) above. The standard deviation of these errors should approximate the root-mean-square deviation from the smoothed values (references 1 and 7).

The standard deviations of the theoretical errors of the position coordinates are defined:

$$\sigma_{\Delta X} = \sqrt{\frac{\sum_1^n \Delta X^2}{n} - \overline{\Delta X}^{\,2}} \quad (7)$$

$$\sigma_{\Delta Z} = \sqrt{\frac{\sum_1^n \Delta Z^2}{n} - \overline{\Delta Z}^{\,2}} \quad (8)$$

where: $\overline{\Delta X} = \dfrac{\sum_1^n \Delta X}{n}$ and $\overline{\Delta Z} = \dfrac{\sum_1^n \Delta Z}{n}$.

The root-mean-square deviation for the X and Z position coordinates is defined:

$$\sqrt{\sum_1^n \frac{(X_{smooth} - X_{actual})^2}{N}} = \Delta X_{rms}. \tag{9}$$

$$\sqrt{\sum_1^n \frac{(Z_{smooth} - Z_{actual})^2}{N}} = \Delta Z_{rms}. \tag{10}$$

n = number of points required to produce curve

In the formulas above, n refers to the number of points required to produce the desired amount of smoothing, and varies from one section to another of the curve as described below.

For computational purposes, the following comparison function, B, is convenient:

$$B = \lim_{(\Delta X_{rms} - \sigma_{\Delta X}) \to 0} \Delta E_x$$

where: $\Delta E_x = \left| \Delta X_{rms} - \sigma_{\Delta X} \right|$.

As a computer procedure, the following has been found to reduce computer time and correspondingly increase computer efficiency.

Attempt to fit the actual X and Z position data points by a 3-point linear least squares curve. Compute this B (B_{23}) and hold this value. Then fit 4-point, 5-point, ..., 12-point linear equations and hold the computed B_{24}, B_{25}, ... , B_{212}. Choose the minimum B_2 and hold the corresponding equation.

Follow the above procedure for a 4-point quadratic least squares curve, computing B_{34}, B_{35}, ..., B_{312}, and hold the minimum B_3 for comparison with B_2. At this point, compare B_2 and B_3 and hold the equation producing the minimum of the two. Continue in this manner through the fitting of a 12-point tenth degree polynomial. (For proper smoothing, use number of points $\geq n + 2$ when fitting an n^{th} degree polynomial.) In moving to the next set of points, an overlap of two points is made to insure continuity.

The resulting function for approximation of smoothed X_s and Z_s values will be sectionally continuous, changing for each set of points.

Computation of Position Coordinates:

Step 1 - Compute slant range:

$$r_{s1}(m) = \frac{(r_o + Y_s)}{\cos\theta} \cos\left[\theta + \sin^{-1}\left(\frac{r_o \cos\theta}{r_o + Y_s}\right)\right].$$

NOTE: All angles should be changed to radians and r_o = 6,373,334.5 m.

Step 2 - Compute Cartesian Coordinates:

$$X_c(m) = r_{s1} \cos\theta \sin\psi \ (m)$$

$$Z_c(m) = r_{s1} \cos\theta \cos\psi \ (m)$$

$$Y_c(m) = r_{s1} \sin\theta.$$

Step 3 - Compute spherical coordinates:

$$X_s = X_c \sin\left[\theta + \sin^{-1}\left(\frac{r_o \cos\theta}{r_o + Y_s}\right)\right]$$

$$Z_s = Z_c \csc\left[\theta + \sin^{-1}\left(\frac{r_o \cos\theta}{r_o + Y_s}\right)\right].$$

NOTE: Make computations, smoothed, for all time points before proceeding.

Computation of wind velocity coordinates:

Step 1 - Compute spherical components:

$$W_{w-e} = U_s(m\ sec^{-1}) = \dot{X}_s$$

$$= \frac{X_{s_{n+1}} - X_{s_{n-1}}}{60\ (t_{n+1} - t_{n-1})} \quad \text{(3-point space averaging)}$$

$$= \frac{X_{s_{n+2}} - X_{s_{n-2}}}{60\ (t_{n+2} - t_{n-2})} \quad \text{(5-point space averaging)}$$

$$W_{s-n} = V_s(m\ sec^{-1}) = \dot{Z}_s$$

$$= \frac{Z_{s_{n+1}} - Z_{s_{n-1}}}{60\ (t_{n+1} - t_{n-1})} \quad \text{(3-point space averaging)}$$

$$= \frac{Z_{s_{n+2}} - Z_{s_{n-2}}}{60\ (t_{n+2} - t_{n-2})} \quad \text{(5-point space averaging)}$$

etc.

Step 2 - Compute spherical wind:

$$W_s(m\ sec^{-1}) = \sqrt{U_s^2 + V_s^2}$$

Step 3 - Compute Cartesian components:

$$W_{(w-e)_c} = U_c(m\ sec^{-1}) = \dot{X}_c$$

Same as in Step 1 except Cartesian Coordinates must be used.

$$W_{(s-n)_c} = V_c(\text{m sec}^{-1}) = \dot{Z}_c$$

NOTE: The finite differences must overlap (i.e., three-point spread: 1st interval, X_{n-1} to X_{n+1}; 2nd interval, X_n to X_{n+2}; 3rd interval, X_{n+1} to X_{n+3}; etc.). This process is called space averaging as defined in Section II. The possibility exists that the value of the constant Δt increment will change from one group of data to the next. Provision must be made for this fact.

Step 4 - Compute Cartesian wind:

$$W_c(\text{m sec}^{-1}) = \sqrt{U_c^2 + V_c^2}$$

Step 5 - Compute spherical wind direction:

$$\xi = \tan^{-1} \frac{U_s}{V_s} + \text{quadrant correction}$$

Step 6 - Quadrant correction:

Using the convention adopted in the paragraph regarding wind position and velocity on page 3, compute the quadrant correction in the following manner:

(a) If $\sin \xi = \frac{U_s}{W_s}$ (+), $\cos \xi = \frac{V_s}{W_s}$ (+), then $\xi w = 180^\circ + \xi$, and $270^\circ \geq \xi w \geq 180^\circ$

(b) If $\sin \xi = \frac{U_s}{W_s}$ (-), $\cos \xi = \frac{V_s}{W_s}$ (+), then $\xi w = 180^\circ - \xi$, and $180^\circ \geq \xi w \geq 90^\circ$

(c) if $\sin \xi = \frac{U_s}{W_s}$ (+), $\cos \xi = \frac{V_s}{W_s}$ (-), then $\xi w = 360^\circ - \xi$, and $360^\circ \geq \xi w \geq 270^\circ$

(d) If $\sin \xi = \frac{U_s}{W_s}$ (-), $\cos \xi = \frac{V_s}{W_s}$ (-), then $\xi w = \xi$, and $90^\circ \geq \xi w \geq 0^\circ$

Transformation of zonal and meridional wind components to vehicle-fixed coordinate systems;

Step 1 - Compute spherical vehicle-fixed coordinate systems:

$$W_{x_s} = U_s \cos(\alpha - 90) - V_s \sin(\alpha - 90)$$

$$W_{z_s} = -U_s \sin(\alpha - 90) - V_s \cos(\alpha - 90)$$

Step 2 - Compute Cartesian vehicle-fixed coordinate systems:

$$W_{x_c} = U_c \cos(\alpha - 90) - V_c \sin(\alpha - 90)$$

$$W_{z_c} = -U_c \sin(\alpha - 90) - V_c \cos(\alpha - 90)$$

Computation of index of refraction (optical)

$$(n-1)10^6 = 77.54 \frac{P}{T} \frac{(\text{mb})}{(^\circ\text{K})} + 37.84 \times 10^4 \frac{e_a}{T^2} \frac{(\text{mb})}{(^\circ\text{K})^2} - 9.66 \frac{e_a}{T} \frac{(\text{mb})}{(^\circ\text{K})}$$

Computation of index of refraction (electromagnetic):

$$(n-1)10^6 = 77.6 \frac{P}{T} \frac{(\text{mb})}{(^\circ\text{K})} + 373256 \frac{e_a}{T^2} \frac{(\text{mb})}{(^\circ\text{K})}$$

NOTE: Make computations above for all time points before proceeding.

A suggested procedure for interpolation from fixed time increments to fixed altitude (250 m) increments follows:

Step 1 - Compute T (Y_s)

Compute T (Y_s) from T (t) and Y_s(t) by linear interpolation.

NOTE: Using the first two time points we linearly extrapolate backward to $Y_s = 0$

Step 2 - Compute p (Y_s)

Compute p (Y_s) from p (t) and $Y_s(t)$ by logarithmic linear interpolation.

NOTE: Using the first two time points we utilize a linear logarithmic extrapolation of the pressure backwards to $Y_s = 0$ (Caution: The logarithm of zero becomes negative infinity.)

Step 3 - Compute r_a (Y_s)

Compute r_a (Y_s) from $r_a(t)$ and $Y_s(t)$ by linear interpolation.

NOTE: The same backward extrapolation scheme should be followed as in Step 1 above.

Step 4 - Compute $e_s(Y_s)$ using $T(Y_s)$ from step 1, Section B above. NOTE: $T(Y_s)$ (^{o}K) must be converted to ^{o}C.

Step 5 - Compute $e_a(Y_s)$ using $r_a(Y_s)$ and $e_s(Y_s)$ from step 2, Section B above.

Step 6 - Using $T(Y_s)$, $p(Y_s)$ and $e_a(Y_s)$ compute $T^*(Y_s)$ from Step 3, Section B above.

Step 7 - Compute $\rho(Y_s)$ using $P(Y_s)$ and $T^*(Y_s)$

Step 8 - Compute $(n(Y_s) - 1)10^6$ from $e_a(Y_s)$, $T(Y_s)$ and $P(Y_s)$ using the formulas above.

Step 9. - Using $U_s(t)$, $V_s(t)$ and $Y_s(t)$ compute $U_s(Y_s)$ and $V_s(Y_s)$ by linear interpolation.

Step 10 - Using $U_s(Y_s)$ and $V_s(Y_s)$ compute W_{x_s} and W_{z_s} using Computation of Wind Velocity Coordinates, Step 1, above.

Step 11 - Using U_s and V_s compute W_s and ξ_w using Computation of Wind Velocity Coordinates, Steps 2 & 5, above.

Step 12 - Using $U_c(t)$, $V_c(t)$ and $Y_c(t)$ compute $U_c(Y_c)$ and $V_c(Y_c)$ by linear interpolation.

Step 13 - Using $U_c(Y_c)$ and $V_c(Y_c)$ compute W_{x_c}, and W_{z_c} using Computation of Wind Velocity Coordinates, Step 2, above.

Step 14 - Compute $(n(Y_s)-1)10^6$ from $P(Y_s)$, $e_a(Y_s)$ and $T(Y_s)$ using formulas above.

Computation of wind shear:

Using $U(Y_s)$ and $V(Y_s)$ interpolated for every 250 m compute shears:

Step 1 - $\Delta U_s = U_{s_{n+1}} - U_{s_n}$ (m)

for every 250 m level

$\Delta V_s = V_{s_{n+1}} - V_{s_n}$ (m)

Step 2 - $S(\sec^{-1}) = \frac{\Delta W}{\Delta h} = \frac{\Delta W}{250} = \sqrt{\frac{\Delta {U_s}^2 + \Delta {V_s}^2}{250}}$

Also at h = 500, 1000, 2000, 3000, 4000 and 5000 m intervals.

Step 3 - Compute ΔW_z and ΔW_x

Using values obtained above, compute:

$$\Delta W_z = W_{z_{n+1}} - W_n$$

$$\Delta W_x = W_{x_{n+1}} - W_{x_n}$$

where $W_{x_{n+1}}$, $W_{z_{n+1}}$, and W_{x_n}, W_{z_n} represent vehicle-fixed spherical coordinates at 250 m levels.

Step 4 - Compute vehicle firing direction referenced shears:

$$S_x(\sec^{-1}) = \frac{\Delta W_x}{\Delta h} = \frac{\Delta W_x}{250}$$

$$S_z(\sec^{-1}) = \frac{\Delta W_z}{\Delta h} = \frac{\Delta W_z}{250}$$

Step 5 - Compute component shears:

$$S_u(\sec^{-1}) = \frac{\Delta U_s}{\Delta h} = \frac{\Delta U_s}{250}$$

$$S_v(\sec^{-1}) = \frac{\Delta V_s}{\Delta h} = \frac{\Delta V_s}{250}$$

NOTE: Use values obtained in Step 1 above. Also, compute S_u and S_v at 500, 1000, 2000, 3000, 4000, and 5000 m intervals.

Display of Final Parameters. Present research and design development programs call for computation of the following parameters from a given radiosonde observation. Display II, following, indicates the approximate print-out form of the computer currently in use, and suggests a convenient form for the printing of the parameter values. Both time and interpolated altitude sequencing are used as variables for ordering the list.

DISPLAY II

Computer Out-put Format

Table I-A - Time Sequenced

Time	T	P	RHO (ρ)	H	PHI(ϕ)	U_C	V_C	Y_C	X_C	Z_C	THETA(θ)	PSI(ψ)
MIN.	°K	MB	KG/M^3	PER	GPM	M/S	M/S	M	M	M	DEG	DEG

Table I-B - Time Sequenced

Time	Y_S	U_S	V_S	W_S	W_C	SIW(ξ)	DER N	DER N	X_S	Z_S
MIN.	M	M/S	M/S	M/S	M/S	DEG	OPT	ELE	M	M

Table II-A - Height Sequenced - Interpolated

Y_S	T	P	H	RHO(ρ)	DER N	U_S	V_S	DER N
M	°K	KP/M^2	PER	KP-S^2/M^4	OPT	M/S	M/S	ELE

Table II-B - Height Sequenced - Interpolated

Y_S	W_S	SIW(ξ)	W_{XS}	W_{ZS}	S	S_X	S_Z	S_U	S_V
M	M/S	DEG	M/S	M/S	1/S	1/S	1/S	1/S	1/S

Table II-C - Height Sequenced

Y	S(500)	S_U(500)	S_V(500)	S(1000)	S_U(1000)	S_V(1000)	S(2000)
M	1/S	1/S	1/S	1/S	1/S	1/S	1/S

S_U(2000)	S_V(2000)
1/S	1/S

Table II-C - Height Sequenced

Y	$S(500)$	$S_U(500)$	$S_V(500)$	$S(1000)$	$S_U(1000)$	$S_V(1000)$	$S(2000)$
M	1/S	1/S	1/S	1/S	1/S	1/S	1/S

$S_U(2000)$	$S_V(2000)$
1/S	1/S

Table II-D - Height Sequenced

Y	$S(3000)$	$S_U(3000)$	$S(4000)$	$S_U(4000)$	$S_V(4000)$	$S(5000)$	$S_U(5000)$	$S_V(5000)$
M	1/S	1/S	1/S	1/S	1/S	1/S	1/S	1/S

Table II-E - Height Sequenced

Y	$S(500)$	$S_X(500)$	$S_Z(500)$	$S(1000)$	$S_X(1000)$	$S_Z(1000)$	$S(2000)$
M	1/S	1/S	1/S	1/S	1/S	1/S	1/S

$S_X(2000)$	$S_Z(2000)$
1/S	1/S

Table II-F - Height Sequenced

Y	$S(3000)$	$S_X(3000)$	$S_Z(3000)$	$S(4000)$	$S_X(4000)$	$S_Z(4000)$	$S(5000)$
M	1/S	1/S	1/S	1/S	1/S	1/S	1/S

$S_X(5000)$	$S_V(5000)$

Table II-G - Height Sequenced - Interpolated

Y_C	U_C	V_C	W_C	W_{XC}	W_{ZC}
M	M/S	M/S	M/S	M/S	M/S

Table III-A - Pressure Sequenced

P	PHI(ϕ)	Y	T	RHO(ρ)
MB	GPM	M	$^\circ$K	KG/M^3

Table III-B - Height Sequenced - Extrapolated

Y	P	T	RHO(ρ)	PHI(ϕ)
M	MB	$^\circ$K	KP-S^2/M^4	GPM

SECTION VI. CONCLUSIONS AND RECOMMENDATIONS

This program is now in use for all space vehicle flight evaluation studies undertaken at the George C. Marshall Space Flight Center. The program was recently used to evaluate the atmospheric parameters utilized in the Saturn (SA-1) flight evaluation with excellent results. This program will be used in all radiosonde data reduction for subsequent space vehicle flights under the direction of the George C. Marshall Space Flight Center.

This radiosonde data reduction technique has many advantages over previous programs. First, smoothing is accomplished by statistically comparing probable error with smoothing differences. Second, the thermodynamic and the wind evaluation programs are combined, forming a continuous sequence of steps and calculations beginning with the raw data and resulting in the desired output. Third, wherever possible, recent studies on the value of the physical constants used in the computations have been incorporated.

Studies concerning the reliability of the parameters determined by the methods of this report are a subject of further investigation. An analysis of errors arising from basic computational procedures, smoothing, instruments, resolutions of plotted ordinates, radiation, etc, is needed for interpretation of the values computed in this report. Adaptions to rawinsonde data obtained with different equipment or presented in different forms are readily possible (e.g., The AM/GMD-2 Rawinsonde System).

APPENDIX

DETERMINATION OF ENVIRONMENTAL PARAMETERS BEYOND THE EXTREME RADIOSONDE HEIGHTS

The purpose of this appendix is to establish a program for the determination of basic environmental parameters above the extreme height of a given radiosonde. These parameters are pressure, temperature, density, and altitude. The purpose of ascertaining these basic environmental parameters, above the extreme height of a given radiosonde, is for flight evaluation studies in connection with space vehicle trajectories and orbits. The method of determining these parameters is by extrapolation. Several conditions are imposed upon this extrapolation. First, the extrapolation can take place only if the radiosonde termination point is at the 15 mb level or above (equivalent to approximately 28 kilometers altitude). If the radiosonde is below the 15 mb level, this extrapolation should not take place unless it is first cleared with the appropriate scientific authority (Aerophysics & Astrophysics Branch, Aeroballistics Division, is the authority for Marshall Space Flight Center) because of the danger of spurious results.

The parameters to be extrapolated from the extreme radiosonde altitude are pressure to 1.0 mb, obtaining standard values at 10, 7, 5, 4, 3, 2, and 1.0 mb. For example, if the radiosonde rises to the 6 mb height, then the extrapolation would be for 5, 4, 3, 2, and 1.0 mb, since the 10 and 7 mb heights are already included in the sounding. The pressure extrapolation must be a logarithmic linear extrapolation. The temperature is extrapolated to 282.66 K by a linear extrapolation using the logarithm of pressure. As in Step 5, Section A.2., the values of density at the corresponding pressure heights are calculated by the following formula:

$$\rho(\text{kpm}^{-3}) = 0.0355252 \, \frac{p(\text{mb})}{T^*({}^{\circ}\text{K})} \tag{1}$$

The hydrostatic equation should be integrated along the logarithmic pressure and linear temperature curves at the standard pressure levels (as in example 6 mb to 5 mb to 4 mb, etc.).

Using Step 3, Section A.3., compute $\emptyset_d$ at 1.0 mb. Using the values in Table B, and the following formulas, calculate pressure, temperature, geopotential height and altitude up to 60,000 geometric meters. (Note: The current meteorological magnetic data tape used for flight evaluation studies at the Marshall Space Flight Center extends considerably beyond the 60,000-meter limit of this print-out).

The temperatures are given by the following formula:

$$T(^{o}K) = T_{MOL_B}\ (^{o}K) + L_M(\tfrac{^{o}K}{m'}) \left[(\phi_d(m') - \phi_{d_B}(m') \right] \qquad (2)$$

where T_{MOL_B}, L_M and ϕ_{d_B} are given in table B (with the exception of ϕ_{d_B} which is computed for the 1.0 mb level).

Pressure is given by the following formulas:

$$P(mb) = P_B(mb) \left[\frac{T_{MOL_B}\ (oK)}{T_{MOL_B}(oK) + L_M(\frac{oK}{m'})\ (\phi_d - \phi_{d_B})} \right]^{\beta/L_M} \text{for } L_M \neq 0 \qquad (3a)$$

$$P(mb) = P_B(mb)\ \exp \left[\frac{\beta(\phi_d(m') - \phi_{d_B}(m'))}{T_{M_B}(oK)} \right] \text{ for } L_M = 0 \qquad (3b)$$

where $\beta = 0.0341648\ \ ^{o}K/m'$

Then using equations (2) and (3a) or (3b) in equation (1) find the density. To find the geometric height use step 4, section A3, of the procedure. These formulas, tables and procedures for parameters above the 1.0 mb level were taken from the ARDC Model 1959 atmosphere and modified slightly to conform to this computation procedure.

The final form of computer output must be at 250 geometric meter intervals. The computer output will be pressure, density, geometric height, temperature, and geopotential height.

TABLE B

ϕ_d(m')	T_{MOL_B} (°K)	L_M(°K/m')
(Height of 1.0 mb level-to be computed)	282.66	
		0.0000
53,000	282.66	
		-0.0045
79,000	165.66	
		0.0000
90,000	165.66	
		+0.0040
105,000	225.66	
		+0.0200
160,000	1,325.66	
		+0.0100
170,000	1,425.66	
		+0.0050
200,000	1,575.66	
		+0.0035
700,000	3,325.66	

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APPROVAL

COMPUTER EVALUATION OF RAWINSONDE DATA
FOR
SPACE VEHICLE APPLICATIONS

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